FINAL TECHNICAL REPORT

A SEARCH FOR LUMINOUS INFRARED GALAXIES

NASA Grant No. NAG 5-1741

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Period Covered
August 15, 1991 to August 14, 1992

Final Technical Report: NAG5-1741

Our one year program to expand the *Search for Luminous Infrared- Galaxies* (NAG 5-1741)[1] was successfully completed, the final result being the compilation of a complete , flux-limited sample of 122 ultraluminous infrared galaxies (ULIRGs), with $f_\nu(60\mu m) > 1\ Jy$, located in the portion of the sky with galactic latitude $|b| > 30°$ and at declination, $\delta \geq -30°$. This new sample represents an order of magnitude increase in the number of ULIRGs over the number of such objects previously identified in the original IRAS Bright Galaxy Survey. The study of the properties of this new sample of ULIRGs represents a large portion of graduate student Dong-Chan Kim's Ph.D. Thesis (Ph.D. expected in 1/95). Three papers that are being submitted to refereed journals have resulted from the work directly supported by this grant.

The bulk of the data analysis supported by NAG5-1741 was carried out by Dong-Chan Kim during his third year of graduate study at the Institute for Astronomy, University of Hawaii. Kim was supported for two full-time summer months, and half-time for nine months during the 1990-91 academic year. The initial stages of this research were carried out during a two-week visit by Kim and the P.I.to the Infrared Processing and Analysis Center (IPAC) at Caltech during September 1991. Candidate lists of ultraluminous infrared galaxies were initially selected from the IRAS Point Source Catalog (PSC–version II) using IPAC software. The lists were cross-correlated with other astronomical catalogs to weed out known galactic objects, primarily reddened stars, molecular cloud cores, and planetary nebula. Overlays were made for the remaining sources (~900) to identify their position on the Palomar Sky Survey (PSS), and photographs were then made to use as finding charts. Approximately 40% of the sources were found to be associated with cataloged galaxies with known redshift, and another 10% with 'infrared-only' identified galaxies or optically identified galaxies with unknown redshift. The remaining objects required optical spectroscopy to determine their type. Previously awarded observing time at Mauna Kea (Sanders, Kim), was used to obtain redshifts for these objects during the course of the grant year. Approximately 70 of the 450 remaining unidentified objects were eventually identified as ultraluminous infrared galaxies.

The second stage of our research began with requests to IPAC for 1-D ADDSCANS for all of the sources in the 1 Jy survey. The ADDSCAN printouts and plots were analysed by hand to determine total fluxes for each source in each wavelength band. The final tables for the ULIRG 1 Jy survey include source positions, total fluxes in the four IRAS bands, infrared colors, and total infrared luminosities obtained using ADDSCAN data.

A full description of the 1 Jy survey of ultraluminous infrared galaxies will be given in Kim & Sanders (1994). This paper includes a complete list of the 122 objects in the survey. Kim & Sanders also determine a new luminosity function for ULIRGs and present evidence for strong evolution in the number density of ULIRGs between z <0.07 and z = 0.07 - 0.25.

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[1] The NASA Technical Officer for this grant is Dr. Donald K. West, NASA Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Space and Earth Sciences Directorate - Code 684, Greenbelt, MD 20771

Publications resulting from this grant:

Kim, D. C. & Sanders D. B. 1994, *The IRAS 1 Jy Survey of Ultraluminous Infrared Galaxies I. The Luminosity Function*, ApJ, submitted

Kim, D. C. & Sanders, D. B. 1994, *The IRAS 1 Jy Survey of Ultraluminous Infrared Galaxies II. Optical, Near-Infrared, and Radio Images*, ApJ, submitted

Kim, D. C., Veilleux, S. V., & Sanders, D. B. 1994, *The IRAS 1 Jy Survey of Ultraluminous Infrared Galaxies III. Optical Spectroscopy*, ApJ, submitted

Kim, D. C. , *Study of a Flux-limited, $F_\nu(60\mu m)$, Sample of Ultraluminous Infrared Galaxies from the IRAS Faint Source Database*, Ph.D. Thesis, University of Hawaii, expected 1/95

Invited Talks - Conference Proceedings:

Sanders, D. B. 1992, *Luminous Infrared Galaxies: Interactions and Environment*, in Relationships Between Active Galactic Nuclei and Starburst Galaxies, ed. A. Filippenko (San Francisco: ASP), pp. 303-316

APPENDIX I

FINAL TECHNICAL REPORT

IRAS (HIRES) STUDIES OF INTERACTING GALAXIES

NASA Grant No. NAG 5-1741, Supplements Nos. 1 & 2

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Our two year program to carry our *IRAS (HIRES) Studies of Interacting Galaxies* (NAG 5-1741, Supplement Nos. 1&2)[1] was successfully completed,

The following tasks were completed during year 1 of the grant:

(1) Complete flux-limited samples of infrared and optically selected interacting galaxies with nuclear separations in the range 1–4′ were compiled. Approximately 40 infrared sources (35 pairs, 5 triples) were selected using optical images that were obtained as part of our study of objects in the *IRAS* Bright Galaxy Samples (Soifer et al.1989, AJ, 98, 766; Sanders et al.1994, AJ, submitted). Several optical surveys were used to select approximately 60 interacting objects, also with nuclear separations in the range 1–4′ .

(2) The required 'training sessions' on how to use and interpret output from *HIRES* were completed by the P.I. and a graduate student who was paid on the grant. Visits to the Infrared Processing and Analysis Center (IPAC) in Pasadena, CA, during December and February for periods of 4 and 3 days respectively, were made in order to meet with IPAC scientists and receive instruction on how to use the *HIRES* package. Several of our sources were processed at IPAC, but due to the amount of interactive processing required in order to understand the nature of possible artifacts introduced by the *HIRES* program, it was decided that we should wait for a decision to be made concerning possible release of the *HIRES* package to remote sites before proceeding with the bulk of our data analysis.

(3) The Institute for Astronomy (supported by this NASA grant) agreed to act as the beta test site for the first exportable version of *HIRES*. A tape version of the program was received and tested during May 1993, and the initial test results were reported at the *HIRES* workshop held at IPAC, 14-16 June, 1993.

First year grant funds were used to pay for two trips to IPAC, and to support one graduate student. A workstation (MacIntosh Quadra 650) was purchased to allow us to process and display HIRES images at the Institute for Astronomy. The bulk of the data processing was actually carried out on a SUN Sparc10. The images were then transfered to the Quadra 650 for display and interactive post-processing.

Second year grant funds were used to purchase a 4.2 GByte disk for long term storage of the HIRES images, and the intermediate data files produced during the HIRES deconvolution. A graduate student was supported for 9 academic months and 2 full time summer months to process the HIRES images. Funds were also used to support two trips to conferences to report initial results of our HIRES analysis.

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The following tasks were completed during year 2 of the grant:

(4) All of our sources (160 interacting galaxies) were processed using the beta test version of HIRES. Images of each source in each of the four IRAS wavelength bands were produced after 10, 20, and 40 iterations of the maximum entropy deconvolution routine.

(5) For those sources at declination $< -40°$, overlays of the deconvolved images were produced and superimposed on the newly released digitized survey of the ESO plates of the southern sky. This procedure greatly enhanced our ability to interpret the HIRES results, for example by allowing us to recognize artifacts in the deconvolution caused by unfavorable scan direction of the detectors across the source. A paper describing the HIRES data processing, and presenting the deconvolved fluxes for the sources is in preparation.

Publications related to this grant:

Sanders, D. B. & Surace, J. 1994, *High Resolution (HIRES) IRAS Imaging of Luminous Infrared Galaxies*, ApJ, in preparation

Jensen, J., Wynn-Williams, C. G., & Sanders, D. B. 1994, *K-Band Imaging of Luminous Infrared Galaxies*, ApJ(Letters), in preparation

Sanders, D. B., & Mirabel, I. F. 1994, *Luminous Infrared Galaxies*, Ann.Rev.Astr.Ap., in preparation

Invited talks - conference proceedings:

Sanders, D. B. 1993, *Luminous Infrared Galaxies* in IAU Symposium 159 – AGNs Across the Electromagnetic Spectrum, (Geneva, Switzerland)

Sanders, D. B. & Kim, D.-C. 1994, *Ultraluminous Infrared Galaxies*, in IAU General Assembly XXII, (The Hague, Netherlands)

Appendix 2

FINAL TECHNICAL REPORT

IRAS (Super Skyflux) Studies of Giant Molecular Clouds

NASA Grant No. NAG 5-1741, Supplement No. 3

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Our one year program to carry out *IRAS (Super Skyflux) Studies of Giant Molecular Clouds* (NAG 5-1741, Supplement No, 3)[1] was successfully completed, the final result being the compilation of background subtracted maps at 12μm, 25μm, 60μm, and 100μmof several nearby giant molecular clouds (GMCs) that have been previously mapped in the millimeterwave line of CO. This project represents a portion of graduate student James Deane's Ph.D. Thesis.

Grant funds were used to support one graduate student for 9 academic months and 2 full time summer months. Funds were also used to purchase a Macintosh Quadra 650 workstation to carry out post-processing display of the Super Skyflux images. An Applewriter Model 630 printer (600 dpi) was purchased to provide high-resolution grey scale display of the resulting images. Support was also provided for one trip to IPAC to consult with Super Skyflux experts on their support staff, and for one conference trip to report our initial results.

The following specific tasks were carried out during the grant year:

(1) The ISSA (Super Skyflux) all-sky image plates were obtained from the NASA National Space Science Data Center (NSSDC) on CD-Rom. A new version of the IRSKY image display package was obtained from IPAC and installed on the IfA computer network. IRSKY was then used to display and interact with the ISSA images. IRSKY is now available on-line to the entire IfA staff.

(2) For each GMC being studied, our CO emission line maps were used to provide an outline of the molecular cloud boundary. The CO maps were then registered and properly overlain on the appropriate ISSA plates (12μm, 25μm, 60μm, and 100μm). The entire $\sim 12^\circ \times 12^\circ$ plate area was then used to determine the background emission. Several different techniques were used to obtain a meaningful fit to the background, and to provide a reasonable approximation of the residuals after background subtraction.

(3) *Spyglass*, a 3-D display program was purchased for use in displaying the infrared flux maps as a function of RA,Dec and ℓ, b. The final background subtracted images for the region surrounding each GMC were stored on CD-rom.

(4) The background subtracted flux maps were reprocessed in order to put the infrared data onto a $6' \times 6'$ grid. These data were then compared with CO data at similar spatial resolution to determine the distribution of luminosity-to-mass, $L_{ir}/M(H_2)$, throughout the GMC. The $L_{ir}/M(H_2)$ ratio is a useful measure of the energetics of the gas. This quantity, along with K-band images, and radio continuum data can be used to estimate the star formation rate. James Deane is currently carrying out a detailed study of the W3 and NGC 7538 GMC's using existing large scale K-band maps previously obtained on Mauna Kea, and published radio continuum

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maps. Two papers will be submitted to the Astrophysical Journal within the next few months.

Publications resulting from this grant:

Deane, J. R., Ladd, E. F. & Sanders, D. B. 1994, *Spatially Resolved Far-Infrared to Molecular Gas Mass Ratios in the W3 GMC*, ApJ, submitted

Deane, J. R., Sanders, D. B., & Ladd, E. F. 1994, *Spatially Resolved $L_{ir}/M(H_2)$ Ratios in the NGC 7538 GMC*, ApJ, in preparation

Invited talks - Conference proceedings:

Deane, J. R., Ladd, E. F., & Sanders, D. B. 1994, *Spatially resolved $L_{ir}/M(H_2)$ Ratios in the W3 GMC*, in Clouds, Cores, and Low Mass Stars, eds. D. Clemens, & R. Barvainis (San Francisco: PASP), pp. 46-50